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Laser beam shape monitoring as a quality control tool in material processing

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Abstract

In the early days of laser processing, monitoring the laser beam quality was done by cardboard or Plexiglas mode burns. More advanced technologies for laser beam diagnostics like scanning systems or camera based systems were developed and introduced into the market, providing higher quality and reproducibility of laser beam analysis as well as giving the potential of quality traceability during product accruement and product life time. Two laser beam caustic measuring concepts will be discussed to show the potential of today's laser beam analysis.

The OnlineBeamMonitor OBM is a camera based, processing head integrated caustic measurement system. The system uses backscattered laser light coming from the protective window of the processing head. Using zoom optics, a complete caustic of the focused laser beam can be measured. During material processing, the backscattered light can be used for simultaneous control of the laser beam quality. The measurement system is directly linked with the laser controller. Evaluation and computation of the measured values will be done in a short timeframe to keep the system updated about the actual spot size and position.

The new FocusMonitor FM+ is system independent. In combination with the new LaserDiagnosticSoftware LDS, monitoring the laser beam quality becomes quicker and easier using automated measuring cycles, fast Ethernet interface and advanced software tools for computation, evaluation and analysis of measured laser beam data. The complete beam caustic can be measured automatically and the characteristic beam parameters like spot diameter, Rayleigh length, beam quality M^2, divergence among will be evaluated from the measurement results.

The benefits of laser beam monitoring in an industrial environment will be discussed. Hereby, a main aspect is the excellent integration capability of measuring device and software into existing data processing networks.

Keywords: Laser Power Measurement, Process Monitoring, Beam Diagnostics, Quality Control

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1. Introduction

One important key factor in laser material processing is the beam quality. The beam quality got direct impact on the focus properties and finally the application results. As better the beam quality is as sharper the laser beam can be focused. Changes in beam quality during the process will directly affect the application result. Thus, laser beam cutting and welding as well as micromachining not only needs high but also most constant beam quality. This implies a necessity to monitor the beam quality frequently during processing application. In the beginning of industrial laser processing, using high power Nd:YAG- or CO_2-lasers, monitoring of the beam quality was done by mode burns in cardboard, thermal-printing paper or PMMR cubes. These are easy to handle but not precise and not easily storable. Apart from this, insanitary fumes and smoke are created by such methods.

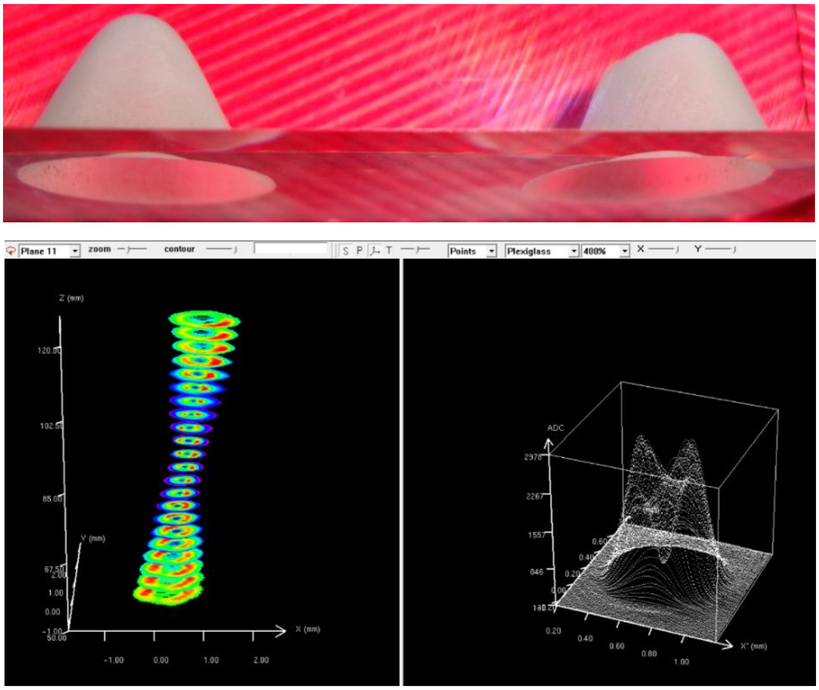

Fig. 1. Mode burn PMMR versus PRIMES LDS “Electronic Plexi”

25 years ago from today, PRIMES GmbH developed a much more advanced method to measure the beam quality by analyzing the caustic of the focused laser beam under full power by using the FocusMonitor FM. The FM principle follows an optical scanning of the laser beam using a rotating pinhole. Two integrated linear axes allows to move the rotating pinhole through the laser beam and along the laser beam axis. Measuring the beam radius and the power density of the beam on a certain numbers of positions below and above the focal plane provides all relevant beam parameters like Rayleigh length Z_R, focal spot diameter 2_{w0}, angle of divergence Θ and last but not least beam the beam propagation ratio M^2 by computation with the LDS, LaserDiagnosticsSoftware. Up to now the FM is used in thousands of industrial laser applications to monitor the laser beam quality of multi kW IR and NIR lasers.

In addition to the FM, PRIMES developed camera based laser beam diagnostic systems for UV, VIS and NIR laser beams like the HP MSM HB, High Power MicroSpotMonitor High Brillance. These devices came into the industry for single mode low power laser beam sources of some 10 Watts up to single mode high power laser radiation in the 10 kW class, application or customer tailored. By means of regular measurements it is, for example, possible to detect and record changes concerning the beam profile the focus position or the focus geometry. The results are most useful for maintenance and error analysis, as well for process optimization in laser material processing. The MicroSpotMonitor is designed for industrial manufacturing environments and thus offers its users a wide range of applications and solutions.
Laser beam quality control in the past includes beam profiling between two shifts or in cases when application results decreased or failed completely. Causes for such failures in processing quality can be degradation of the laser source, damages of the beam guiding system, as well as on the processing head optics or simply contamination. Decreased laser beam quality and / or focal shift sometimes lead to production break downs. Today's demands are measuring beam quality more frequently, best as on-line measurement during processing. In combination with PC-network or field bus integration, storage of the catched processing data supports the quality reporting during production for traceability. With this background, new developments with enhanced features for laser beam shape monitoring will be introduced in the following.

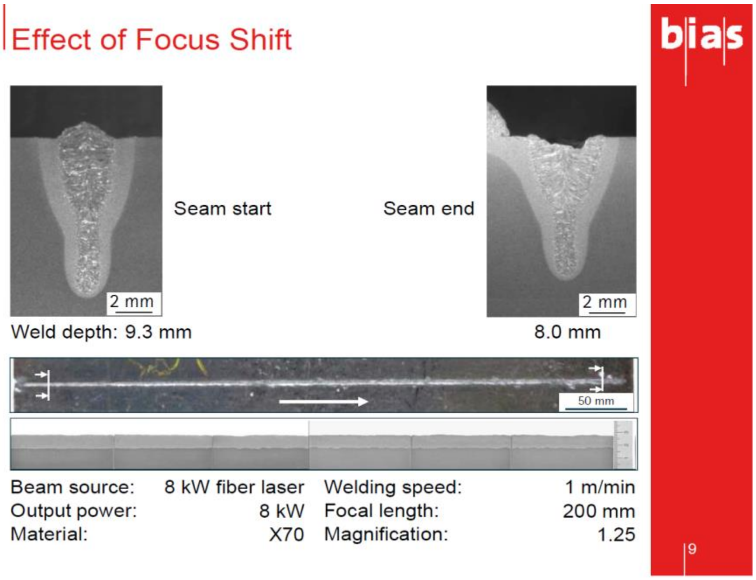

Fig. 2. Influence of focus shift to processing result

2. Improvements in optical scanning Measurements

The PRIMES FM, the FocusMonitor, used for the analysis of continuous wave laser beams between 10 W up to 50 kW. The system measures the beam properties of the focused radiation used for laser materials processing like welding, cutting, drilling, cladding and as well in the field of rapid manufacturing, also known as 3-D-Printing.

The FM, now evolved into the FM+, providing new electronic features to meet the current and future demands of signal processing and long term statistics and evaluation. A new main board with a 16 bit AD converter instead of the previously used 12 bit and improved detector units enable better cycle times and systems accuracy. The FM+ is equipped with an Ethernet interface for fast and secure data exchange with the PowerMonitor PM or other PRIMES devices or any corresponding computer running the PRIMES LaserDiagnosticsSoftware (LDS). The new mechanical design allows the FM+ to be mounted overhead or sideways.

Fig. 3. The new PRIMES FM 120+

2.1. Measuring Procedure – the Principle

The laser beam is scanned using a specialized measuring tip within a 3D measurement space. A small pin hole (typical diameter: 20 µm) in the measuring tip samples a small part of the laser beam. The diameter of the pin holes geometry and design must match the given laser beam specifications.
Focused CO_2-laser radiation typically has a low divergence, as well most solid state lasers like fiber or disk lasers. Diode lasers can have low or high divergence of the focused laser beam depending on the type of the diode laser. Application tailored measuring tips are available to serve all the various divergences, wavelengths and laser power levels.
The sampled part of the laser beam is guided by two reflecting mirrors to the detector unit. The type of detector depends on the power and wavelength of the laser radiation. For different wavelengths, pyroelectric detectors or photodiodes are available.
The high speed of the rotating measuring tip enables the analysis of high power densities. Due to the high dynamic range of the employed analog digital converter, a very good signal-to-noise ratio is achieved.
High peak intensities as well as very low intensities are displayed precisely and simultaneously. This is essential for automatic measurements of caustics near or in the focal plane over at least four Rayleigh lengths according to ISO 11146. The power density along the laser beam axis varies at least by the factor 4 in this measurement stroke. However, the signal-to-noise ratio must be > 40. Detectors with higher dynamic ranges up to 85 dB support this requirement.

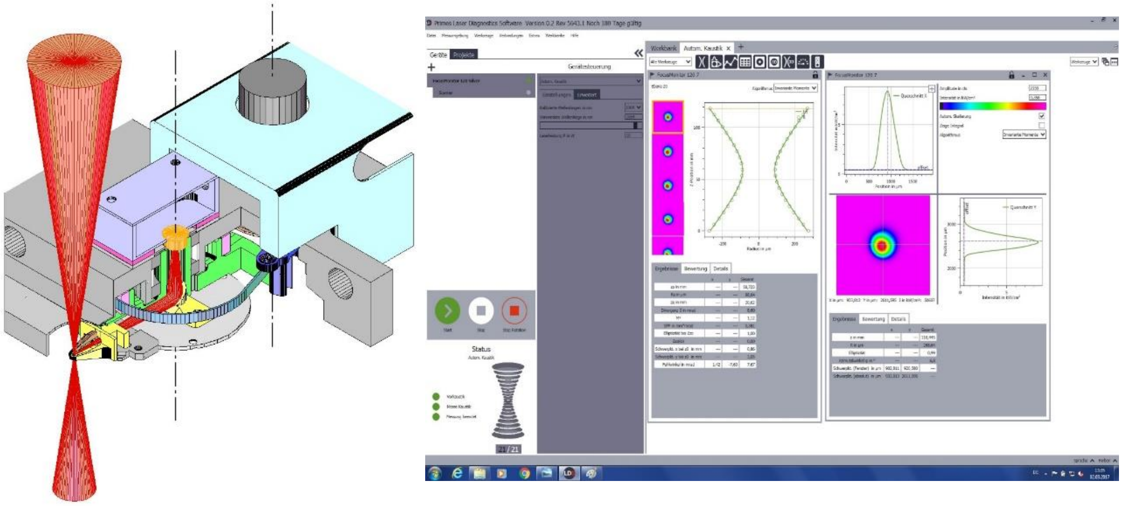

Fig. 4. Measurement principle of FM+ plus diagnostics result

Please note that hardly no laser beam power is absorbed, more than 99 % of the optical power pass the measurement device and needs to be absorbed separately by using a PRIMES PowerMonitor, such as PM 48 or PM 100 or CPM.

2.2. Operation

The FM120+ communicates with computers or system controls via Ethernet connection. The PC-based LaserDiagnosticsSoftware LDS 2.9 enables manual or semi-automatic measurement of the beam distribution as well as the determination of the beam position and the beam dimensions. Beam waist diameter, divergence angle, Rayleigh length and beam quality factor M² are examples of properties, which will be calculated by the LDS 2.9 based on the measuring results from the FM+.
The selected resolution of the detector and the size of the measuring window can be adjusted within the software. The integrated z-axis of the FM+ enables the automatic measurement of complete caustics over four Rayleigh lengths. The number of measurement planes is freely selectable, typically recommended 16 and 22 planes. Complete measurement data sets and computation results can be stored and loaded for further measurements with specified basic data sets as a reference.
The next generation LDS 3 will fully optimize the functionality of the FM+. In addition to the faster data transmission (Ethernet), the connection to the LDS 3 is a major advantage of the FM+ compared to the FM. The LDS 3 offers new possibilities to characterize laser beams and advanced features such as the automatic measurement of caustics. Measurements with higher resolutions and freely selectable ROI can be recorded. Furthermore, the FM+ has a higher analogue to digital resolution, which makes it possible to determine beam radii even under critical or limited signal – to - noise ratio.

Advantages of FM+ and LDS 3:

- Fast Ethernet data transmission
- Automatic set up and parameter selection
- Automatic caustic measurement (start button principle)
- Higher resolution
- Freely selectable ROI
- Higher signal to noise ratio

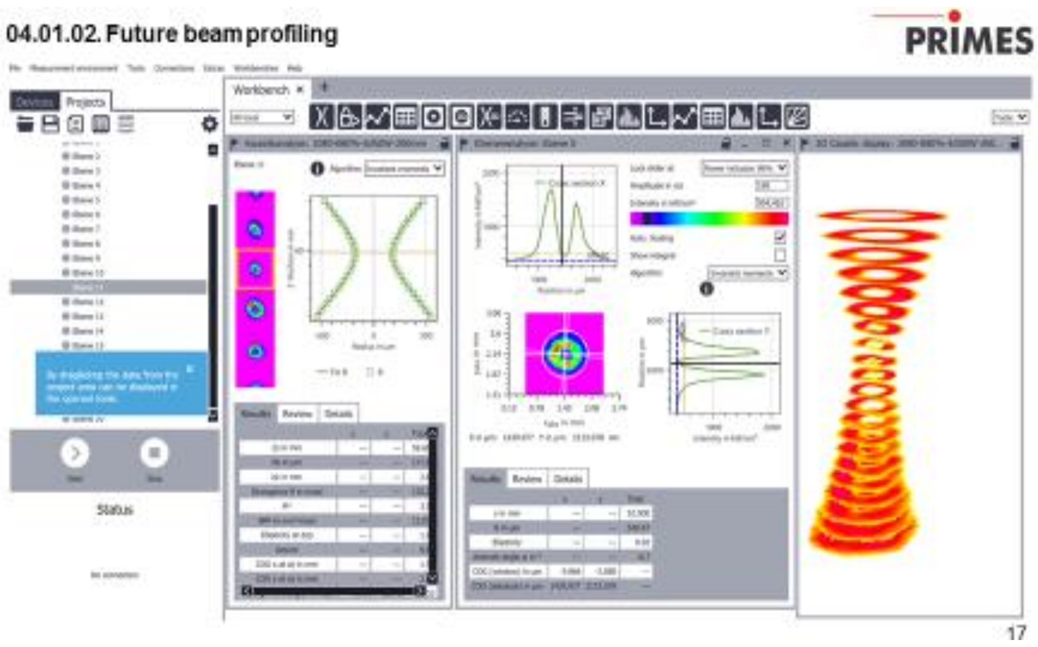

Fig. 5. Screen shot of LDS 3.0 - Application tailored ring mode profile

2.3. Measuring Tips and Detectors

The FM+ needs to be equipped with the “right” measuring tip and the “right” detector combination. The replacement of both the detector and the measuring tip will be done within a few minutes. For the wavelength λ = 10.6 µm of the CO_2 lasers, mainly pyroelectric detectors, such as the DFCM, together with HP- CO_2 measuring tips came into use.
For the analysis of most fiber guided solid-state lasers in the range between 800 and 1100 nm, the highly dynamic detector DFIG-PS with an automatic signal adjustment should be assembled. These detectors are generally combined with any of the HighDiv YAG measuring tips. There are additional DL measuring tips for diode lasers, which are mostly highly divergent. In addition, specially adapted detectors, e.g. with an

optimum signal-to-noise ratio or measuring tips with increased or reduced sensitivities in a wide range can be supplied.
Accurate evaluation provides information on alignments problems, thermal impact of optical components and seriously contamination or damages to any beam guiding or processing optical element.

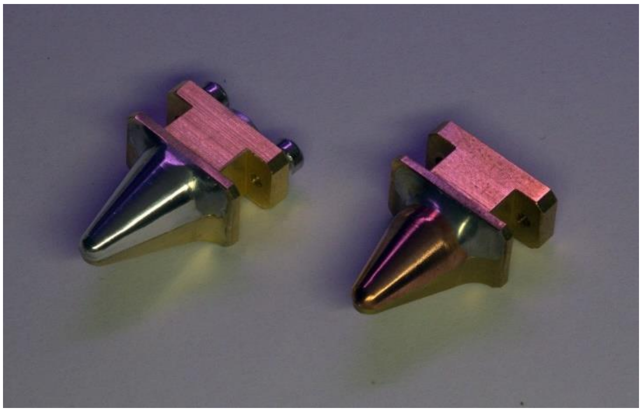

Fig. 6. Measuring tips for FM+

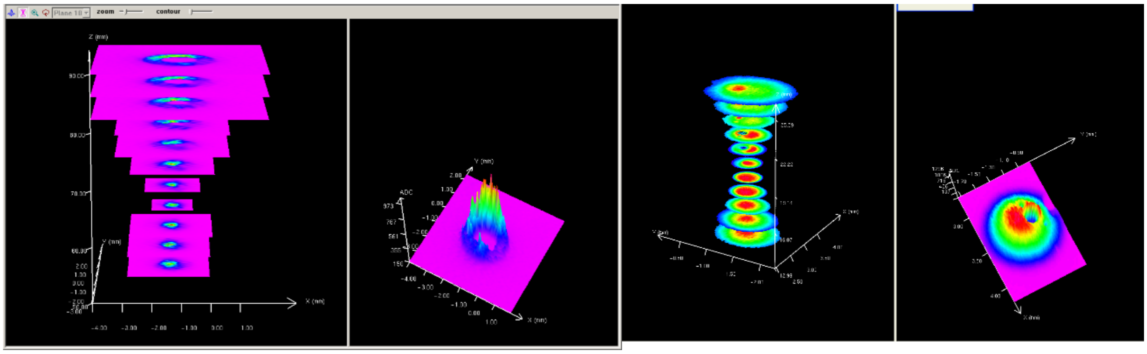

Fig. 7-8. Error tracking, contaminated protection window (left), damaged collimating optic (right)

2.4. *Configurations FM+*

The mechanical axis of the FM+ enable a measurement window of minimum 8 x 8 mm (optionally 12 x 12 mm). The vertical stroke of 120 mm solves most applications. Software features allows even a virtual stroke of several meter, especially for the upcoming scanning heads. The measurable focus diameter ranges from 100 to 1000 micron. Measurable Rayleigh lengths could reach 25 mm. Thus, the FM+ enables the measurement of a wide range of laser sources for various fields of applications.

3. On-line beam monitoring

3.1. Optics integrated beam shape measuring

With most beam parameter monitoring systems, the beam is either passed through or absorbed by the measurement system. Thus, during the measurement, the laser beam cannot be used for processing. Sometimes beam profiling takes longer than the manufacturing cycle time. In a worst case scenario, the measured beam parameters can therefore differ from those during processing. Ideally, a simultaneous measurement of the beam during processing is desired. In this way the measurement result is a true image of the working beam at the time of processing.

One method of on-line beam parameter monitoring is the use of a beam splitter in the laser processing head. Ideally situated behind the focusing lens, the beam splitter can direct a very small proportion (<1%) of the laser beam power towards a sensor element such as a CCD chip. Provided that the beam paths from the beam splitter to the focal point of the processing head and to the CCD chip are identical, the image on the CCD chip is a "twin" of the focal spot. A shift in the focal position caused by thermally induced focus shift is registered as a variation in spot size on the CCD chip. The back reflection from the protective window is utilized to measure the focus geometry. The reflected light is directed onto the sensor element using a high quality beam splitter.

In order to verify this method of beam parameter monitoring, a new developed OnlineBeamMonitor (OBM) was set up. Here, measurements were taken with a PRIMES FocusMonitor directly in the focal plane and compared to the measurement results from the OBM. The measurements were carried out using a 5 kW TRUMPF disk laser with a modified BEO D70 processing head. The two sampling methods bear a very close correlation as shown in 10, with the largest deviation being 6% of the measured Rayleigh length of the laser in the 3000 W range.

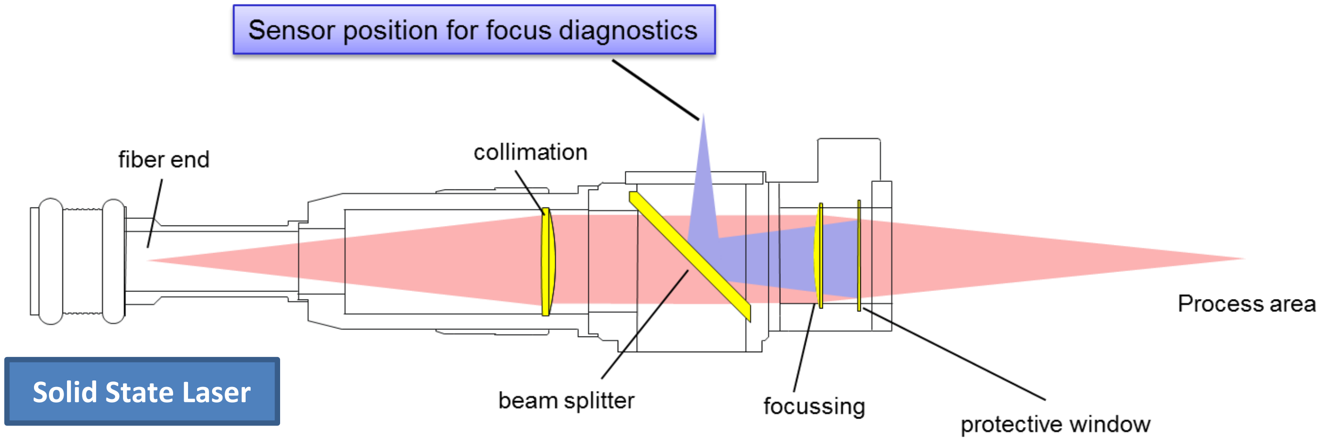

Fig. 9. On-line Beam Monitoring example setup

As this setup is integrated into the processing head, it is specially adapted to one type of mechanical design. Cooperation with systems manufacturers and processing heads experts will be necessary in order to integrate on-line beam monitoring into other designs. Currently, a cooperation between the companies TRUMPF and PRIMES has produced the on-line beam monitoring tool "Smart Beam Control".

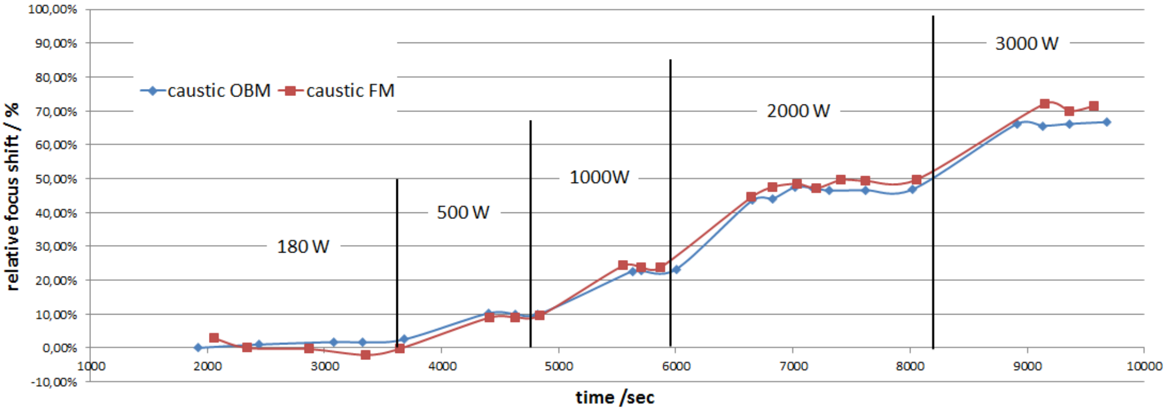

Fig. 10. Comparison of measurements with a FocusMonitor vs. OBM

3.2. "Smart Beam Control"

The TRUMPF Smart Beam Control system was developed for integration into laser cutting heads on flat-bed 2D cutting machines. In order to minimize additional mass and volume to the cutting head, only the sensor element was attached. Data processing and beam calculations occur in a separate unit within the control cabinet. Contrary to the OBM design the protective window is tilted, eliminating the need for a separate beam splitter to extract the reflected beam and to minimize the optical elements. A schematic principle set-up can be seen in figure 11. The sensor is available as an optional add-on. This enables a standardized production of the cutting head, where the sensor is only mounted when required.

Using the movable zoom optics within the cutting head the focus position, and therefore the relative measurement position of the sensor, can be adjusted, enabling the measurement of a full beam caustic within the space of 1 minute. During processing, the diameter of the image on the CCD sensor is monitored and kept constant by controlling the zoom optics. Any thermal effects leading to a focus shift can therefore be counteracted immediately.

As the measurement routines are integrated directly into the control panel of the laser machine, they are activated by running these routines and require no specific knowledge of the machine operator regarding beam diagnostics. The measurement history is stored locally and can be used for condition monitoring and life cycle analysis. Also, cutting samples for the exact determination of focus position and size are no longer necessary, which saves material.

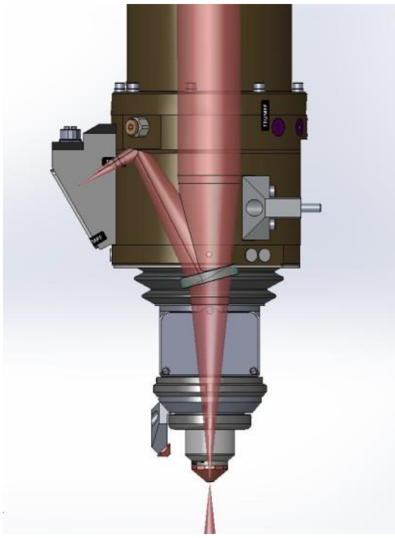

Fig. 11. Online Beam Monitoring

The laser beam processing system does not require additional external diagnostics hardware to generate the parameter data base.

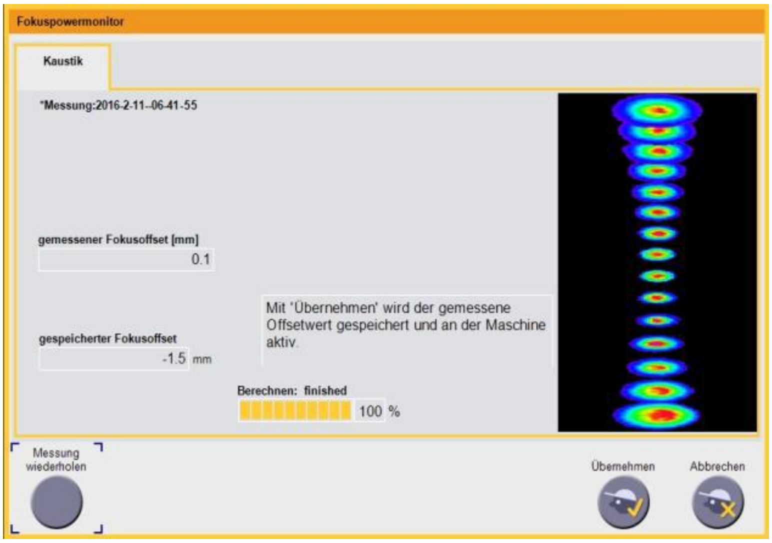

Fig. 12. Sample measurement of Smart Beam Control on a simplified operators screen

The shown sample measurement was recorded with Smart Beam Control directly on the control panel of the TRUMPF machine. These caustic measurements can either be done manually or after certain set time intervals, similar to other machine inspections additionally to the automatic online monitoring of one selected plane. Depending on the measurement results, the system can provide action measures for the correction of any beam deviations.

4. Summary

Higher number of human less laser beam applications, combined with strategical aspects of the upcoming Industry 4.0 leads to furthermore variations of beam profiling instruments. First developments allow an optimistic market view. But more complex laser system does not replace the human laser know how.
Please keep on exploring and elaborating the laser beam technology. Perfection might be one goal, new applications the other one.

Keep your ambitions
Thank you